The Main Conditions Ensured Problemless Implementation of ^{235}U High Enriched Fuel in Kozloduy NPP (Bulgaria) – WWER-1000 Units

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Introduction

Nowadays the economic performance improving of nuclear power plants is usually accompanied by corresponding usage of UO_2 fuel with higher content of ^{235}U (4,0%-4,5%). The passing to this kind of fuel increases the neutron flux in the centre of the core which determines a core's higher duty. As a consequence power output is reached and, in parallel, refueling outages have consistently become shorter in duration. The final results are increased fuel burnup which ensures the decrease of the fuel costs.

After M. S. Chatterton [1]: "By implementation of high burnup or high fuel duty or both in some Westinghouse PWRs a series of fuel issues with safety significance occurred." …"These unexpected fuel issues have been experienced as Axial Offset Anomaly (AOA), incomplete control rod insertion (IRI) events, high crud buildup and oxidation levels, and fuel failures, particularly those involving higher than predicted oxidation". The explanation of the root causes of these events was the reason for the efforts and the worldwide interest in investigations and discussions concerning these events and especially the Axial Offset Anomaly (AOA) or its synonym Crud Induced Power Shift (CIPS), which are used for the indication of the phenomena of the abnormal power shift that occurs in some high duty core Pressurized Water Reactors.

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In the frame of the Contract 13801 between IAEA and Institute for Nuclear Research and Nuclear Energy – BAS, Sofia, as a part of the Agency's CRP "Optimization of Water Chemistry Technologies and Management to Ensure Reliable Fuel Performance at High Burnup and in Ageing Plants – FUWAC 2006-2009"), it was carried out evaluation of the experience by burnup extensions (implementations of ^{235}U higher enriched fuel) in PWRs and it was concluded that higher duty cores are always attended with the onset of sub-cooled nucleate boiling (SNB) on the fuel cladding surfaces and the initial excess reactivity of core. The main consequences of these basic factors are the modifications of chemical/electrochemical environments of the nuclear fuel cladding- and reactor coolant system- surfaces.

It was found that **an explicit result of the synergic impact of the boiling- and water radiolysis- processes** on the Pressurized Water Reactor fuel cladding surface areas **is the change of fuel cladding chemical environment from reducing (hydrogen rich) to oxidizing**, which is the most important, with dramatically consequences, change [2].

This circumstance was evaluated as determining the requirement that the nuclear fuel cladding materials in PWRs and WWERs operating with SNB, should have high corrosion resistance by this modification of chemical and electrochemical environment. As such kinds of suitable fuel cladding materials are selected and recommended [3], [4] the Russian fuel cladding material E 110 (Zr1Nb), French fuel cladding material M5^{TM} and partially ZIRLO^{TM} (Westinghouse) which have much higher corrosion resistance than Zircaloy-4 (Zry-4).

The application of these selected cladding materials was recommended as a prerequisite for the reliable fuel assembly performance by high duty core PWRs and WWERs.

The application of UO_2 fuel with higher content of ^{235}U causes higher initial reactivity in a PWR core by beginning of cycle. By classical way of the compensation of initial reactivity, as neutron absorber H_3BO_3 dissolved in reactor coolant is used. In this case the required coolant H_3BO_3 concentration is higher. In some cases the neutralization of boric acid with alkalizing agents is problematic as a consequence of limitation of their adding in coolant. The insufficient neutralization with alkalizing agents of the coolant boric acid determines the high temperature coolant pH values to be below $pH_{300} = 7.0$, which favors the corrosion processes in reactor coolant system and an increase in the quantity of coolant corrosion products. The coolant corrosion products form on the cladding surfaces porous deposits with thickness up to 100 µm. Such kinds of deposits, by presence of SNB, are transformed in nickel oxide and become a matrix for boron hideout, causing the abnormal power shift - CIPS (AOA) phenomena.

It is clear that the initial excess reactivity in core does not have a direct impact on coolant water chemistry but depends mainly on the way of compensation of initial excess reactivity in core.

The implementation of solid burnable absorbers Gd_2O_3 allows decrease of the coolant H_3BO_3 concentration at the beginning of cycle [5] and makes it neutralization problemless.

At the base of the above mentioned about main changes and consequences by burnup extensions through application of ^{235}U higher enriched fuel in PWRs and WWERs it was found one realistic way for reliable plant performance by this significant technological improving. **The fundaments of this way are the application of fuel cladding materials which are enough corrosion resistant in the nuclear fuel cladding environment in PWRs and WWERs operating with SNB;**

and

the implementation of solid neutron burnable absorbers together with the dissolved in coolant neutron absorber – natural boric acid. ***By the passing to burnup extension of WWER-1000 Units in NPP Kozloduy – Bulgaria these criteria were fulfilled through implementation of the Russian advanced fuel assemblies TVSA (Fig.1) in which the fuel cladding material is E 110 (Zr1Nb) and Gd_2O_3 as burnable neutron absorber is integrated in fuel.***[6]

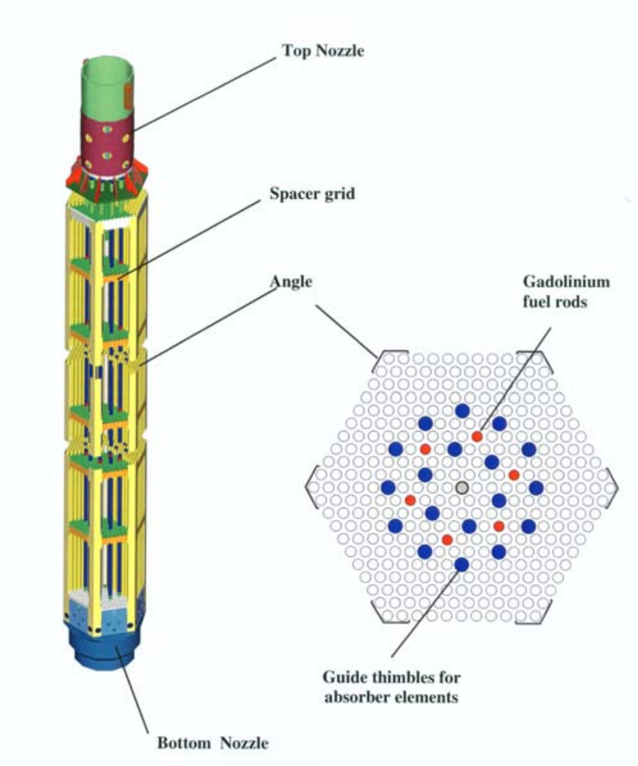


Fig.1 TVSA general view and cartogram [6].

The limitation of constructional materials corrosion processes in primary circuit (mainly fuel element claddings and steam generators tubing) which ensures the real minimizing of the fuel cladding depositions (to 10 µm clad corrosion product thickness) **is the significant goal of the coolant water chemistry.** The most important **requirement** of coolant water chemistry for WWER-1000 Units is that the **coolant** $\mathbf{pH_{300}}$ **values** must always be between $\mathbf{pH_{300} = 7.0}$ **and** $\mathbf{pH_{300} = 7.2}$.

This requirement is the fundament of *the recent NPP Kozloduy (WWER-1000 Units) water chemistry primary circuit guidelines.* After these guidelines the main coolant chemical parameters are the total coolant alkalizing agent (Li, K, N) concentrations as functions of coolant boric acid concentrations. The required relations between these parameters are expressed in compact form in Fig.2 in Table 1, in which the reactor operation levels as functions of the limit's deviations are given.

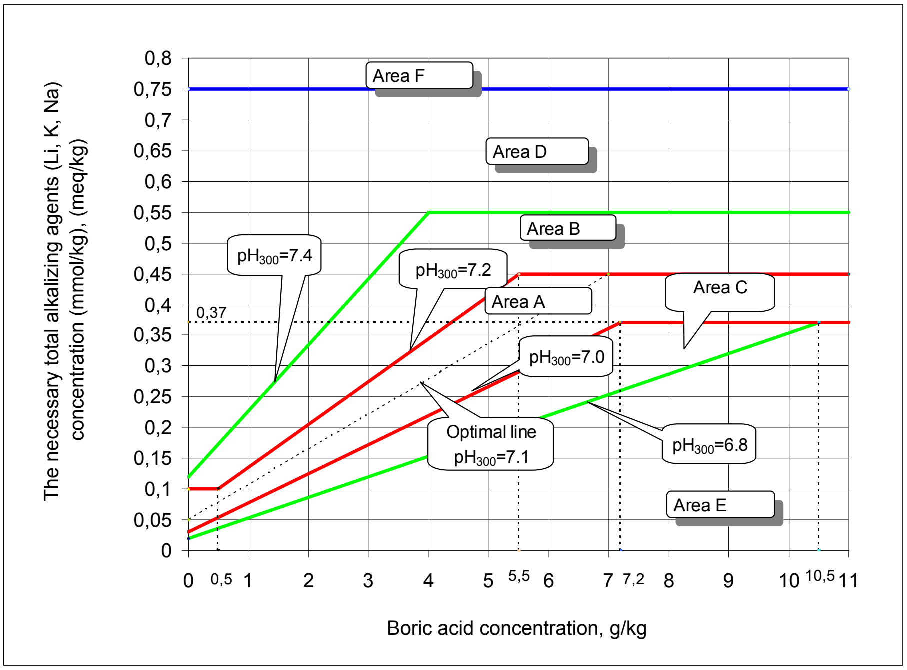


Fig.2. WWER-1000 Primary Circuit Water Chemistry Guideline Requirements (Kozloduy NPP).

Table 1. Required (bulk) Coolant pH_{300} as Results of Coolant Boric Acid Concentrations and Total Coolant Alkalizing Agent Concentrations / Operation Levels

		Limits Deviations		
Chemical Parameters	Limit	1 level (7 days)	2 level (24 hours →MCPL)	3 level (cold condition)
Total coolant alkalizing agents (K, Li, Na) concentration, mmol/kg as f(H_3BO_3)	Area A $pH_{(300)}= 7.0\div7.2$	Area B $pH_{(300)}= 7.2\div7.4$ Area C $pH_{(300)}= 6.8\div7.0$	Area D $pH_{(300)} >7.4$ Area E $pH_{(300)} < 6.8$	Area F

The main water chemistry plant data for the full operation periods of first three fuel cycles (12-th, 13-th, 14-th), by which step-by-step implementation of TVSA fuel assemblies in Unit 5 of NPP Kozloduy was realized, **showed** undoubtedly that practically the *water chemistry guideline requirements* **were kept** - The coolant pH_{300} values are always in the frame of Area A. Under these conditions the collected coolant radiochemistry plant data showed that it had been ensured fully acceptable low level of the nuclide activities in coolant. This indicates that the corrosion rates of out-of-core materials were enough limited and as a consequence the activity buildup in primary circuit (a result of re-deposition of activated corrosion products on out-of-core surfaces) was restricted. (**Only one exception** was observed during the second part of 13-th fuel cycle (beginning of February 2007), when the coolant pH_{300} values are decreased below

7.0, near to 6.8. As an answer of these pH value changes (with duration about 4-5 days), the specific activities of all nuclides in coolant increased up to 2 order higher.

If it can be seen from the data - Fig.3 and Fig.4a & Fig.4b for the whole operation period of the **15-th fuel cycle** of Unit 5 when there are **100% TVSA fuel assemblies in reactor core**, the coolant **water chemistry plant data values are always in the frame of Area A**:

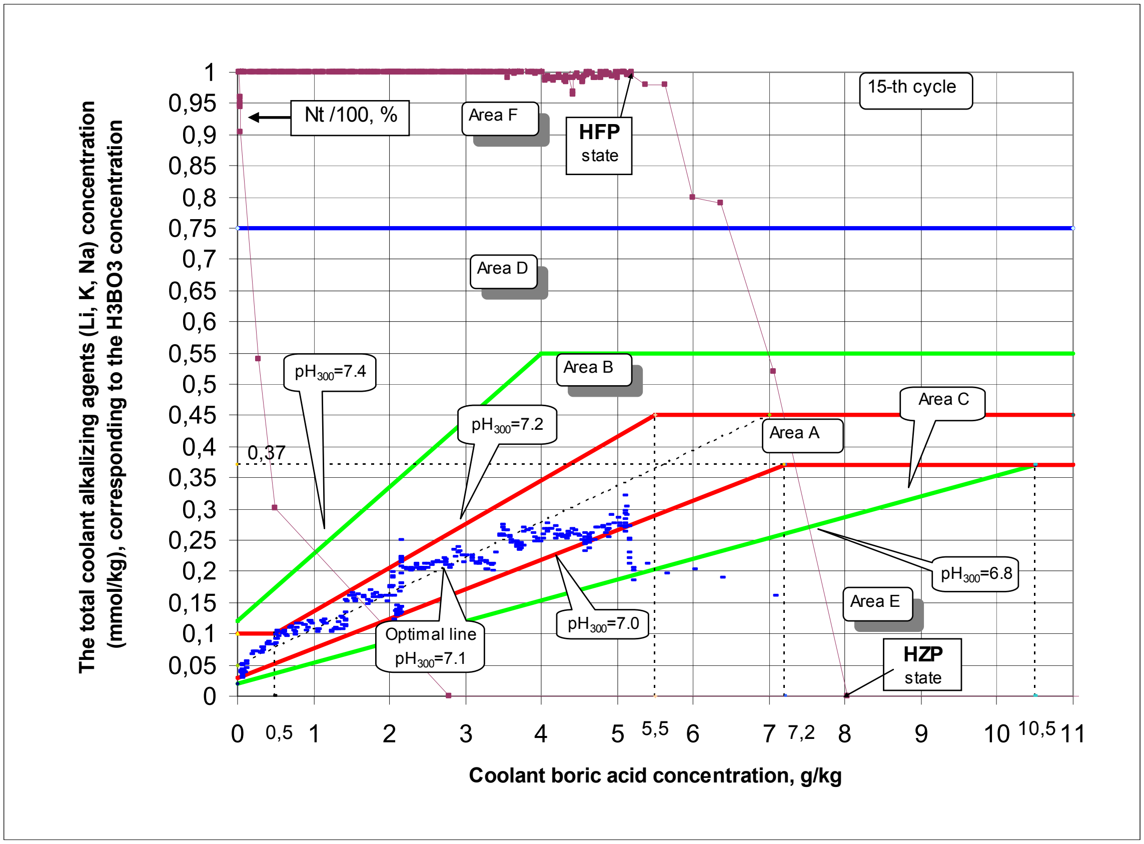
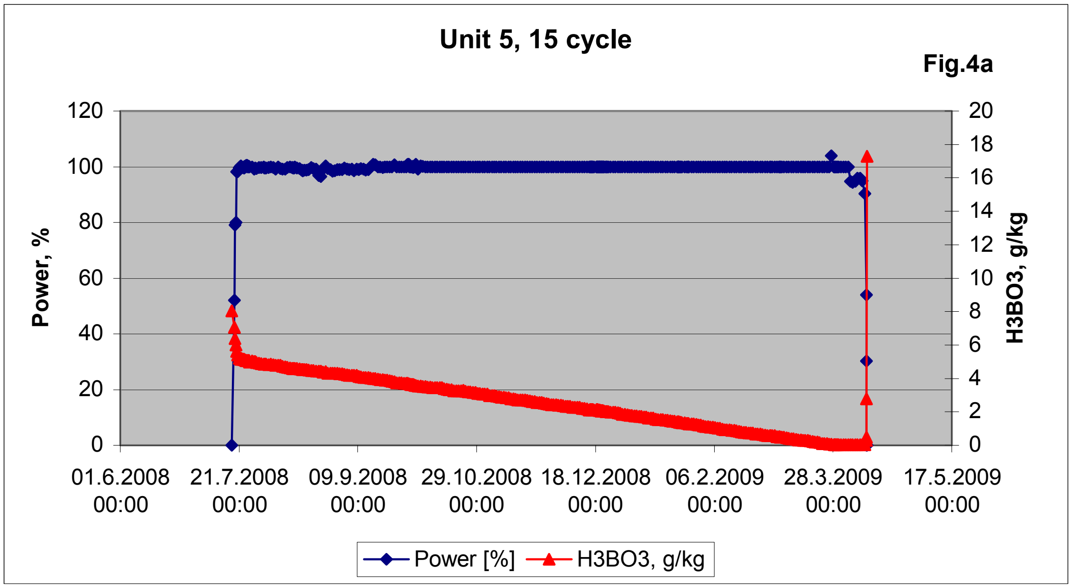


Fig.3 Coolant Water Chemistry Plant Data for the whole 15-th Fuel Cycle of Unit 5 (Time period 18.07.2008 up to 11.04.2009)



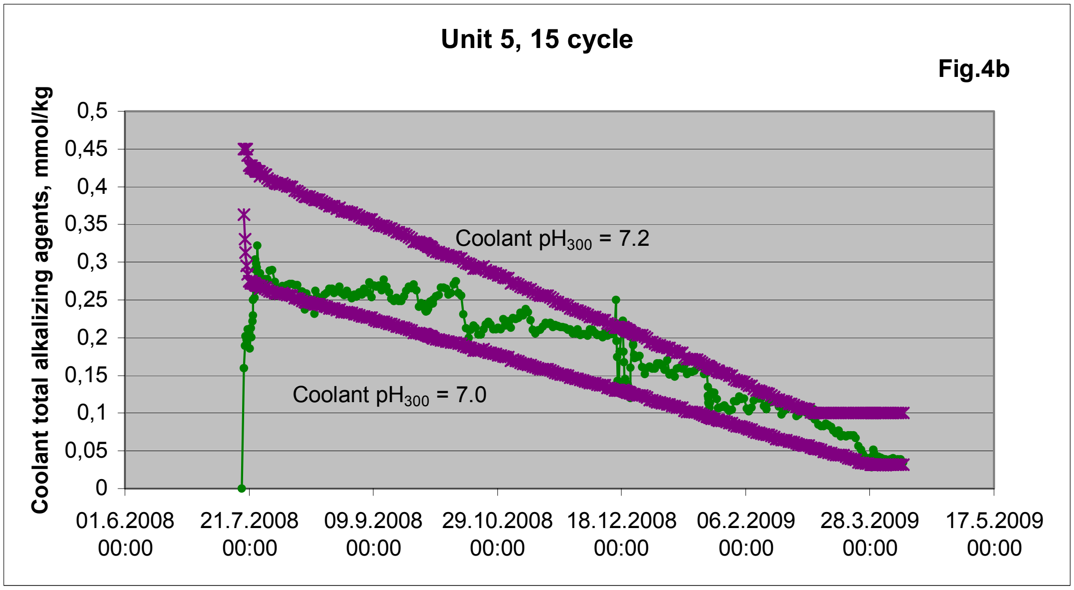


Fig.4a & Fig.4b. Water chemistry & reactor power time synchronous data for the whole 15-th Fuel Cycle, Unit 5 (Time period 18.07.2008 up to 11.04.2009)

This very important fact should be evaluated as a confirmation that the requirement coolant water chemistry plant data to be kept in the frame of Area A, is fully realizable by 100% TVSA fuel assemblies in reactor core.

The data represented in Fig.5 allow the conclusion to be made that **the coolant activated corrosion product characteristics during the whole operation period of the 15-th fuel cycle**, **Unit 5,** are practically on the same low level, as the 14-th fuel cycle, Unit 5, i.e. by 100% TVSA fuel assemblies in reactor core, an increase of coolant corrosion aggressiveness can not be indicated.

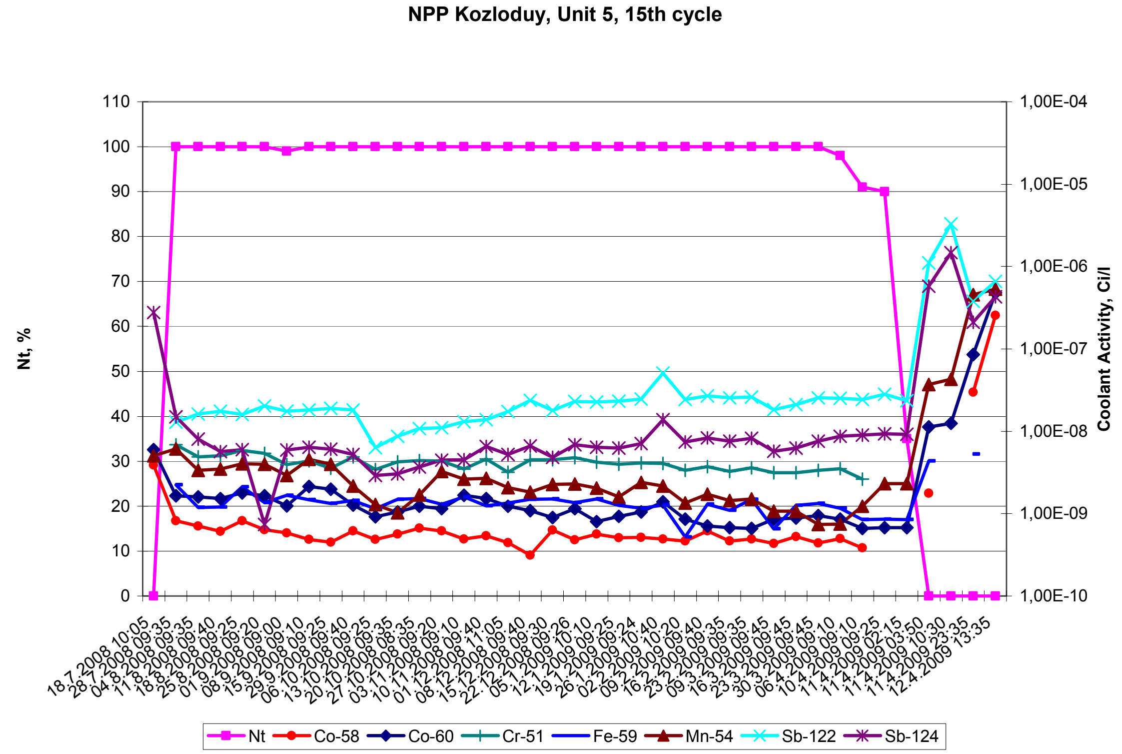


Fig.5 Coolant activated corrosion products for the whole operation period of the 15th fuel cycle, Unit 5, Kozloduy NPP

Practically excellent radiochemistry coolant plant data, obtained also during the whole operation period of the 15-th fuel cycle, Unit 5, are a good confirmation for the effectiveness of the developed and applied in WWER-1000 Units in NPP Kozloduy, coolant water chemistry whose main characteristic is the keeping of the variations of coolant $pH_{(300)}$ *values in the frame of 7.0 – 7.2.*

The experiences of fuel cycles 12-th, 13-th, 14-th and 15-th of Unit 5 allow this coolant water chemistry to be recommended for application in all next fuel cycles of Unit 5 and Unit 6 in NPP Kolzoduy which will be realized again with gadolinia doped uranium fuel - TVSA fuel assemblies.

The water chemistry plant data of 15-th fuel cycle of Unit 5, when in the reactor core are all together 163 TVSA fuel assemblies (240 fuel rod – FR with ^{235}U 4,4% enrichment, 66 FR with ^{235}U 4,0% enrichment and 6 FR with 5% Gd_2O_3), confirm the conclusion *that the recommended by Kurchatov Institute- Moscow changes (an extension of the permitted limit of total alkalizing concentration in coolant from 0,45mmol/kg to 0,50mmol/kg) in water chemistry guidelines* ***are not necessary***.

As exceptional important coolant water chemistry data were evaluated the data for the Beginning of Cycle (BOC) period (the period between Hot Zero Power – HZP and Hot Full Power – HFP states).

In the case of the 15-th fuel cycle the BOC period is shorter (about 3 days only) than the BOCs periods (about 7 days) of the fuel cycles 12-th, 13-th and 14-th. This fact confirms the success of the Unit's 5 staff's efforts to overcome the unacceptable longer time of BOC period.

The relatively low coolant pH_{300} during BOC periods always has as a consequence temporary increase of coolant activities. This fact was the reason for the evaluation that the cases of pH_{300} values below $pH_{300} = 7.0$ during BOC are unacceptable.

For the overcome of this situation objective conditions exist because there is enough large reserve for the increase of alkalizing agents doze in coolant without possibility to reach the limited doze of alkalizing agents – 0.45mmol/kg.

General Conclusion:

The collected water chemistry and radiochemistry data during the operation of WWER-1000 Units in NPP Kozloduy (Unit 5) for the period 2006-2009 (12-th, 13-th 14-th and 15-th fuel cycles) undoubtedly indicate for WWER-1000 Units, whose specific features are:

- Steam generators with austenitic stainless steel 08Cr18N10T tubing;
- Steam generators are with horizontal straight tubing;
- Fuel elements cladding material is Zr-1%Nb (Zr1Nb) alloy;

that one realistic way for problemless implementation of ^{235}U high enriched fuel have been found.

The main feature characteristics of this way are:

- Implementation of solid neutron burnable absorbers together with the dissolved in coolant neutron absorber – natural boric acid;
- Application of fuel cladding materials with enough corrosion resistance by the specific fuel cladding environment created by presence of SNB;
- Keeping of suitable coolant water chemistry which ensures low corrosion rates of core- and out-of-core- materials and limits in core (cladding) depositions and restricts out-of-core radioactivity buildup.

The realization of this way in WWER-1000 Units in NPP Kozloduy was practically carried out through:

- **The implementation of Russian fuel assemblies TVSA** which:
  - o have as fuel cladding material E-110 alloy (Zr1Nb) with enough high corrosion resistance by presence of sub-cooled nucleate boiling (SNB);
  - o use burnable absorber (Gd) integrated in the uranium-gadolinium ($U\text{-}Gd_2O_3$) fuel (fuel rod with 5.0% Gd_2O_3).
- Development and implementation of **water chemistry primary circuit guidelines**, which require the relation between boric acid concentration and total alkalizing agent concentrations to ensure coolant $pH_{300} = 7.0 – 7.2$ values during the whole operation period.

The above mentioned conditions by the passing of WWER-1000 Units in NPP Kozloduy to uranium fuel with 4.4% ^{235}U (TVSA fuel assemblies) practically ensured **avoidance of the creation of the necessary conditions for AOA onset**. (The operational experience (2006-2009) of NPP Kozloduy Unit 5 practically **confirms our prognosis** (2006-2007) for the possibility AOA to be avoided by implementation of ^{235} U higher enriched fuel in WWER-1000 Units).

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